Modeling of ice algal and pelagic production and air-sea CO2 exchange in the Arctic Ocean

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Abstract In the Arctic Ocean, both phytoplankton and sea ice algae are important contributors to the primary production and the arctic food web. Copepod in the arctic regions have developed their feeding habit depending on the timing between the ice algal bloom and the subsequent phytoplankton bloom. A mismatch of the timing due to climate changes could have dramatic consequences on the food web as shown by some regional observations. In this study, a global coupled ice-ocean-ecosystem model was used to assess the seasonality of the ice algal and phytoplankton blooms in the arctic. The ice-ocean ecosystem modules are fully coupled in the physical model POP-CICE (Parallel Ocean Program- Los Alamos Sea Ice Model). The model results are compared with various observations. The modeled ice and ocean carbon production were analyzed by regions and their linkage to the physical environment changes (such as changes of ice concentration and water temperature, and light intensity etc.) between low- and high-ice years. A model sensitivity run is conducted to investigate how sea ice permeability of gas may change the model bias in the arctic basin.

1. Introduction of global ice-ocean-ecosystem model

We have developed a 3-D ice-ocean-ecosystem model (Jin et al., 2008) by coupling with the Los Alamos National Laboratory (LANL) Parallel Ocean Program (POP, http://climate.lanl.gov/Models/) and sea ice model (CICE, Hunke and Lipscomb, 2008). The ecosystem model (flowchart shown in Figure 1) consists components in sea ice (Jin et al., 2006, 2007 and 2009) and in ocean (revised from Moore et al., 2004).

The sea ice ecosystem includes ice algae, NO3, NH4 and Si. The ocean ecosystem includes phytoplankton (diatom, small phytoplankton and diazotroph) in terms of C, Chl and Fe; diatom in Si; nutrients (NO3, NH4, Si, Fe and PO4); zooplankton and others (DON, DOC, DOP, DOFe, DIC, O2, Alkalinity, CaCO3, DMS, DMSP, DMSPP, sea surface pCO2).

The POP-CICE model grid has a varying spatial resolution of 40km in polar area (displaced North Pole in Greenland) to about 1 degree in the equatorial area. There are 40 vertical layers from 10m at surface to 250m in the bottom. The initial conditions for the ocean T, S and NO3 are from WOA 2005, and the initial conditions for the sea ice model are from model runs by Hunke and Bitz (2009). The meteorological forcing are from 6-hourly NCEP reanalysis data. The ice algal ecosystem model in CICE alone with a simple slab ocean model was validated (Deal et al., 2011) before we fully coupled the POP-CICE and ice-ocean ecosystem models. The model results of the pan-arctic area are shown here.

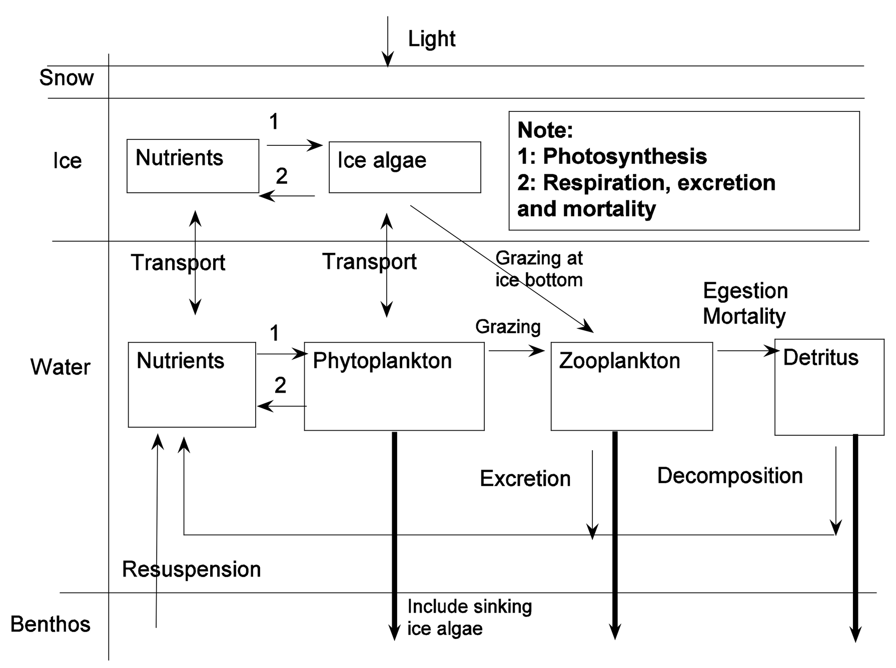

Figure 1. Flowchart of coupled ice-ocean ecosystem model

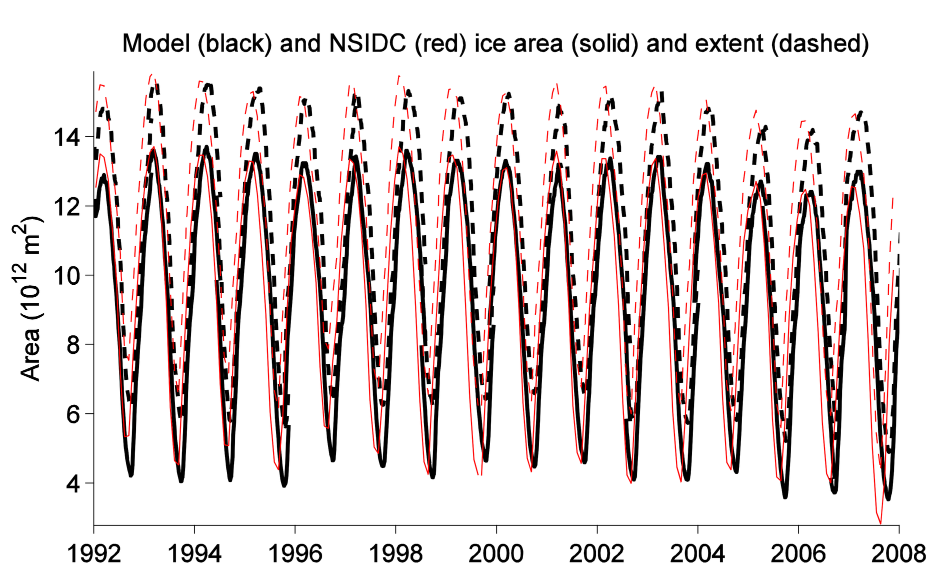

Figure **5. The model results compare well with NSIDC sea ice area and extent during the model period of 1992-2007.**

2 Spring Chl concentration

In sea ice

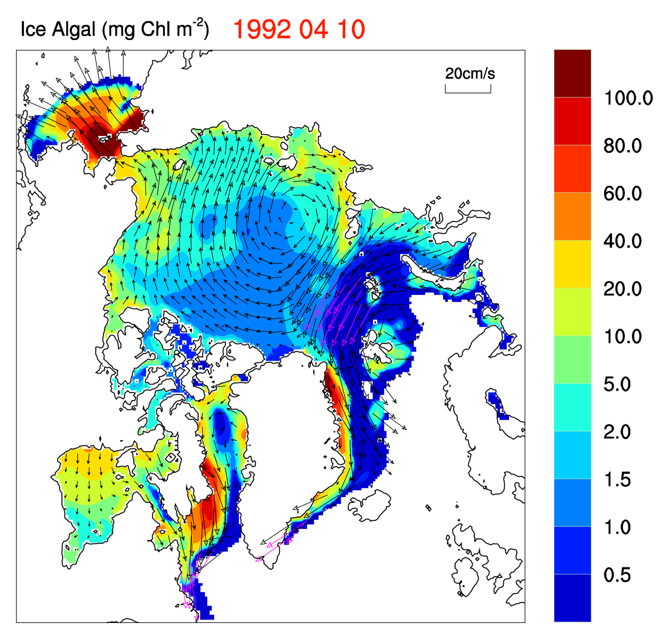

Figure 3.The Chl concentration in sea icein April: production is moving to the north, regional difference may be caused by light intensity, ice growth rate and nutrients availability.

In upper ocean

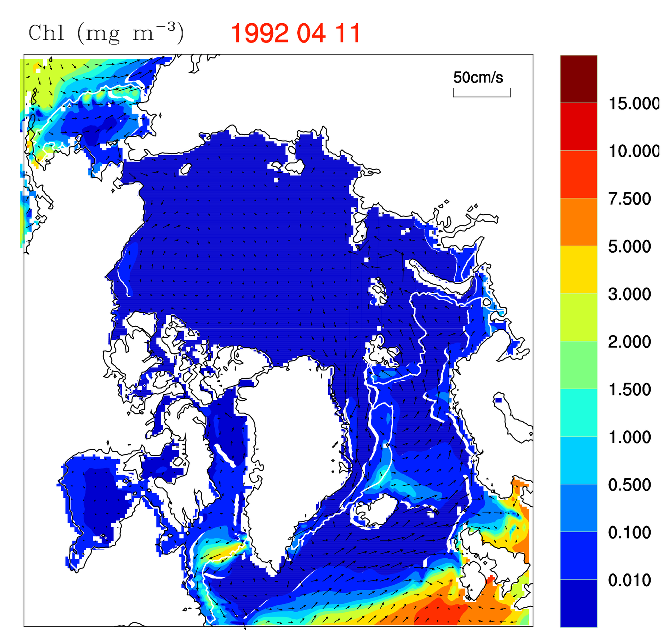

Figure 4.The Chl concentration in upper ocean in April: production is moving north to the ice edge. Ice edge phytoplankton bloom is shown in the Bering Sea and Labrador Sea.

3 Interannual variations of sea ice area and primary production

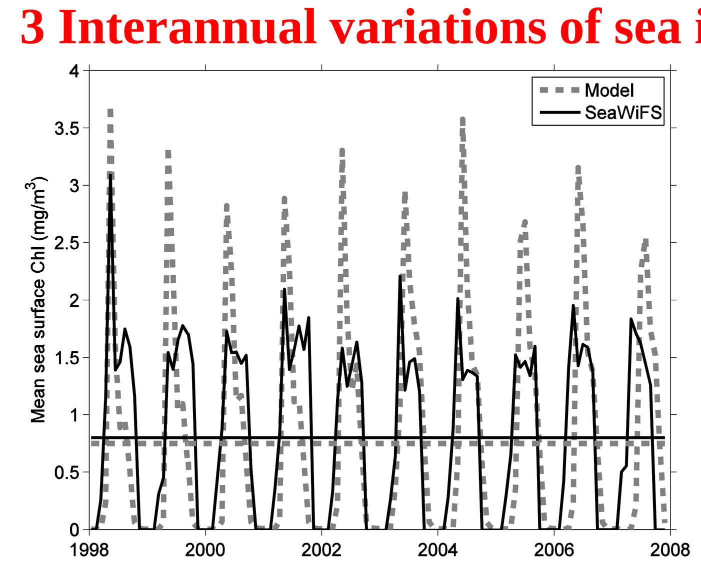

Figure 5. Comparison of modeled and SeaWiFS monthly mean sea surface Chl-a in the open water within the Arctic Circle (north of 66.56 N). The two horizontal lines are the long-term (1998-2007) mean of the modeled and SeaWiFS Chl-a.M

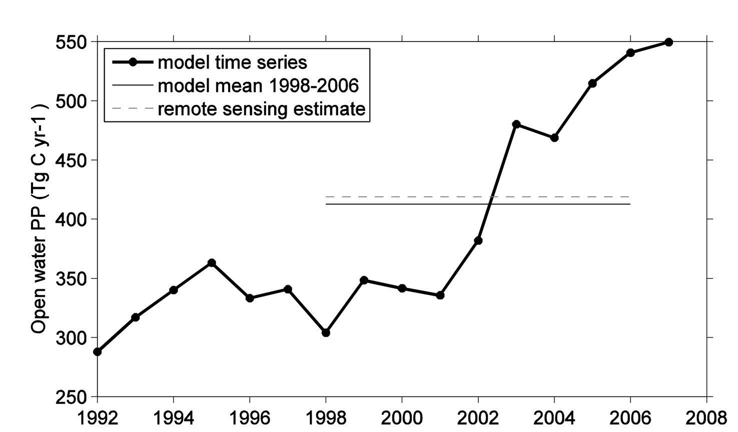

Figure 6**. Time series of modeled annual upper ocean 100m integrated primary production in the open water within the Arctic Circle (north of 66.56N). The mean open water upper 100m primary production of 1998-2006 was estimated using remote sensing Chl a and an algorithm developed for the Arctic by Pabi et al., (2008).**

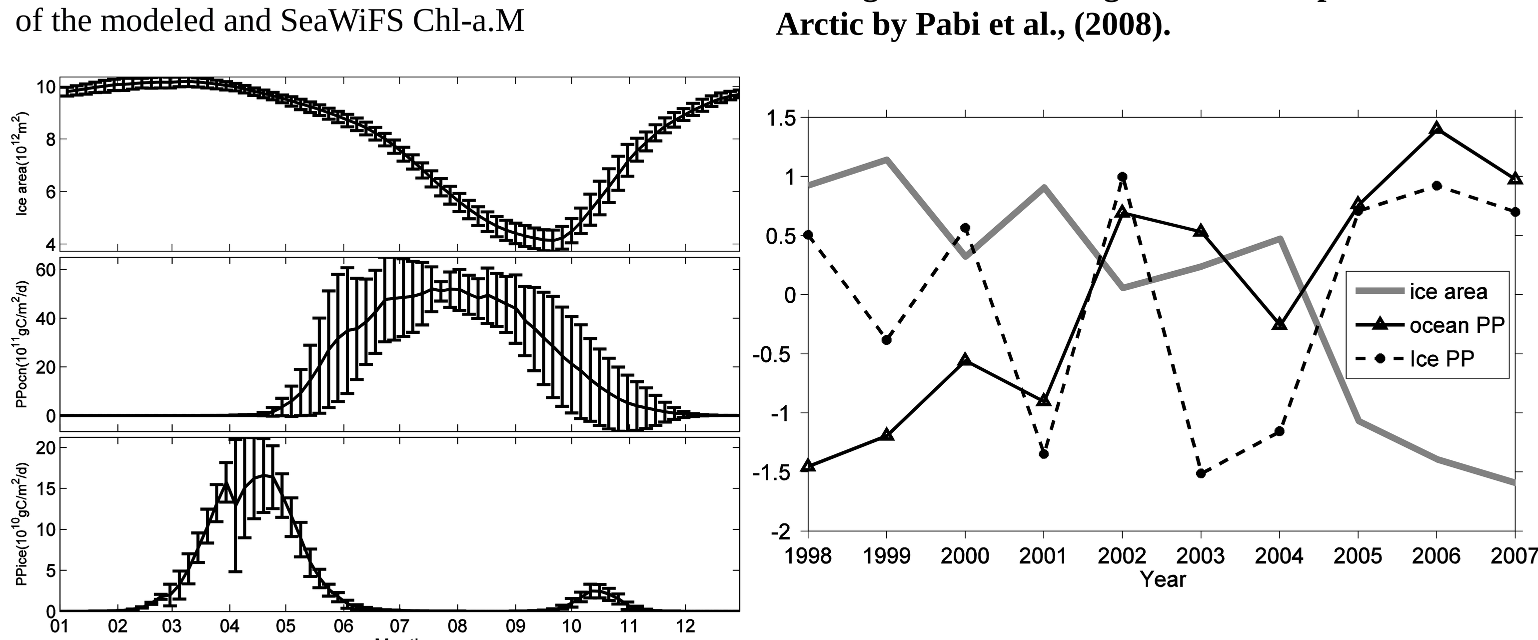

Figure 7. Time series of modeled sea ice area, upper ocean 100m integrated primary production and sea ice algal prodution within the Arctic Circle: a) mean seasonal cycle of 1998-2007 and standard deviation, b) normalized annual production. The normalization was done by minus the mean and divided by the standard deviation of the time series.

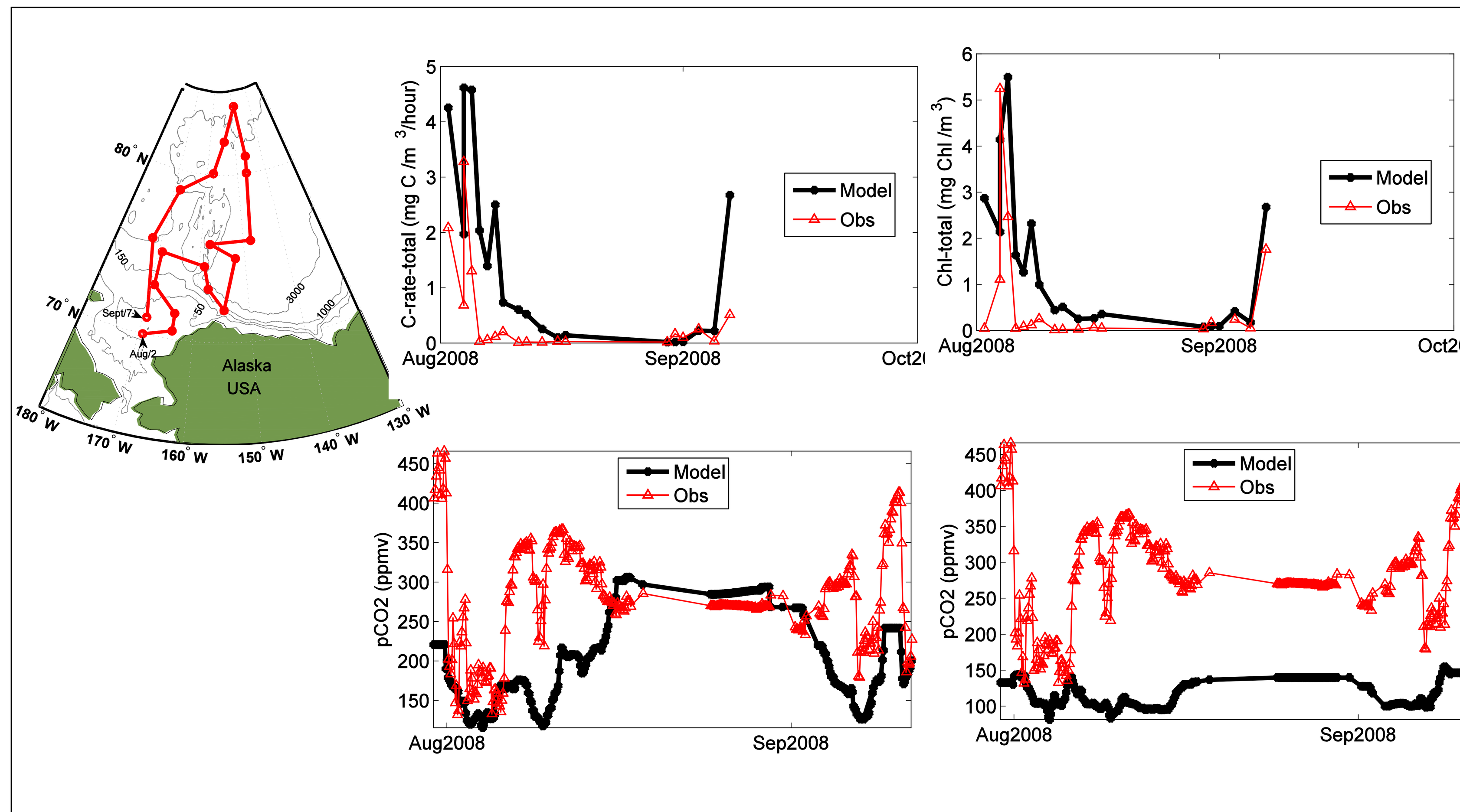

Figure 8. Model-data comparison of a) total carbon production rate, b) total Chl a in sea surface 10m, c) sea surface pCO2 with increased sea ice permeability and d) same as c) but without increased sea ice permeability

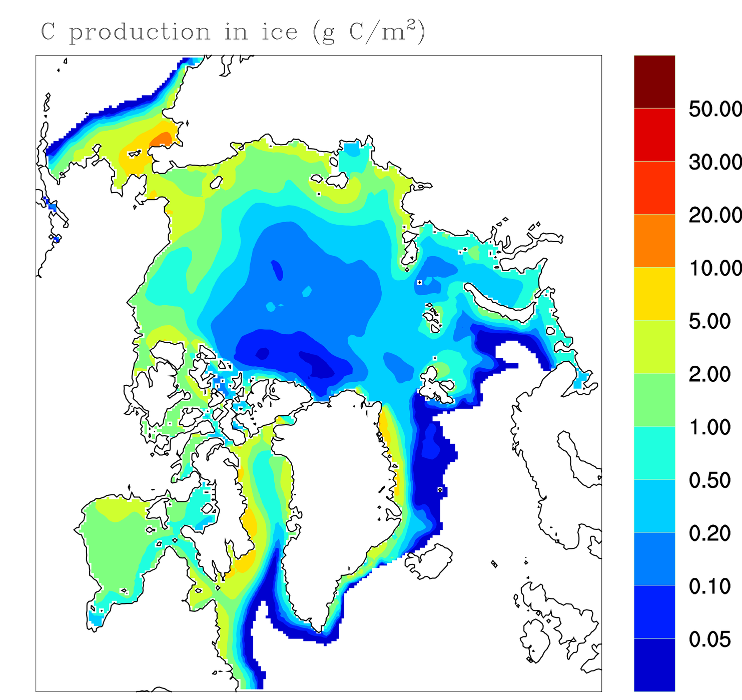

Figure 9.Annual primary production of sea ice algae.

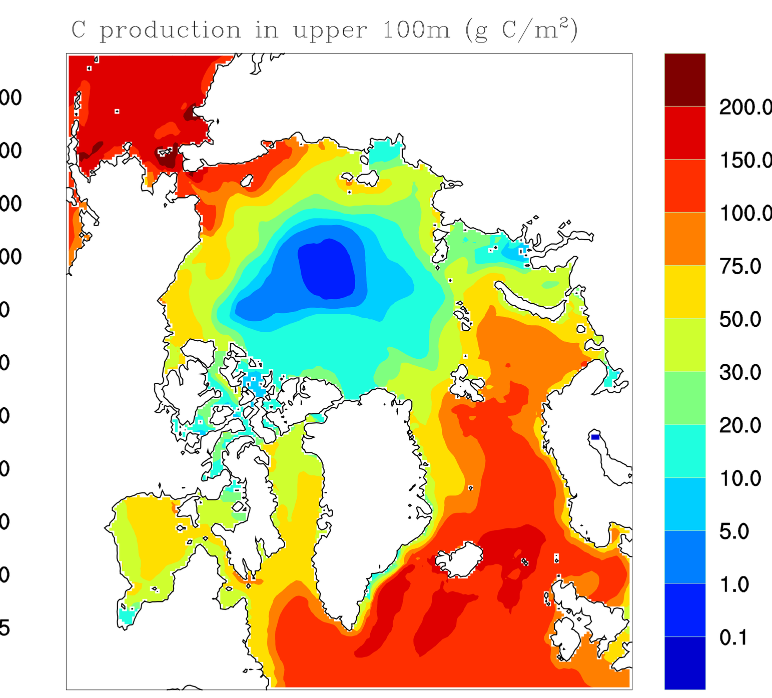

Figure 10.Upper 100m integrated annual primary production of phytoplankton.

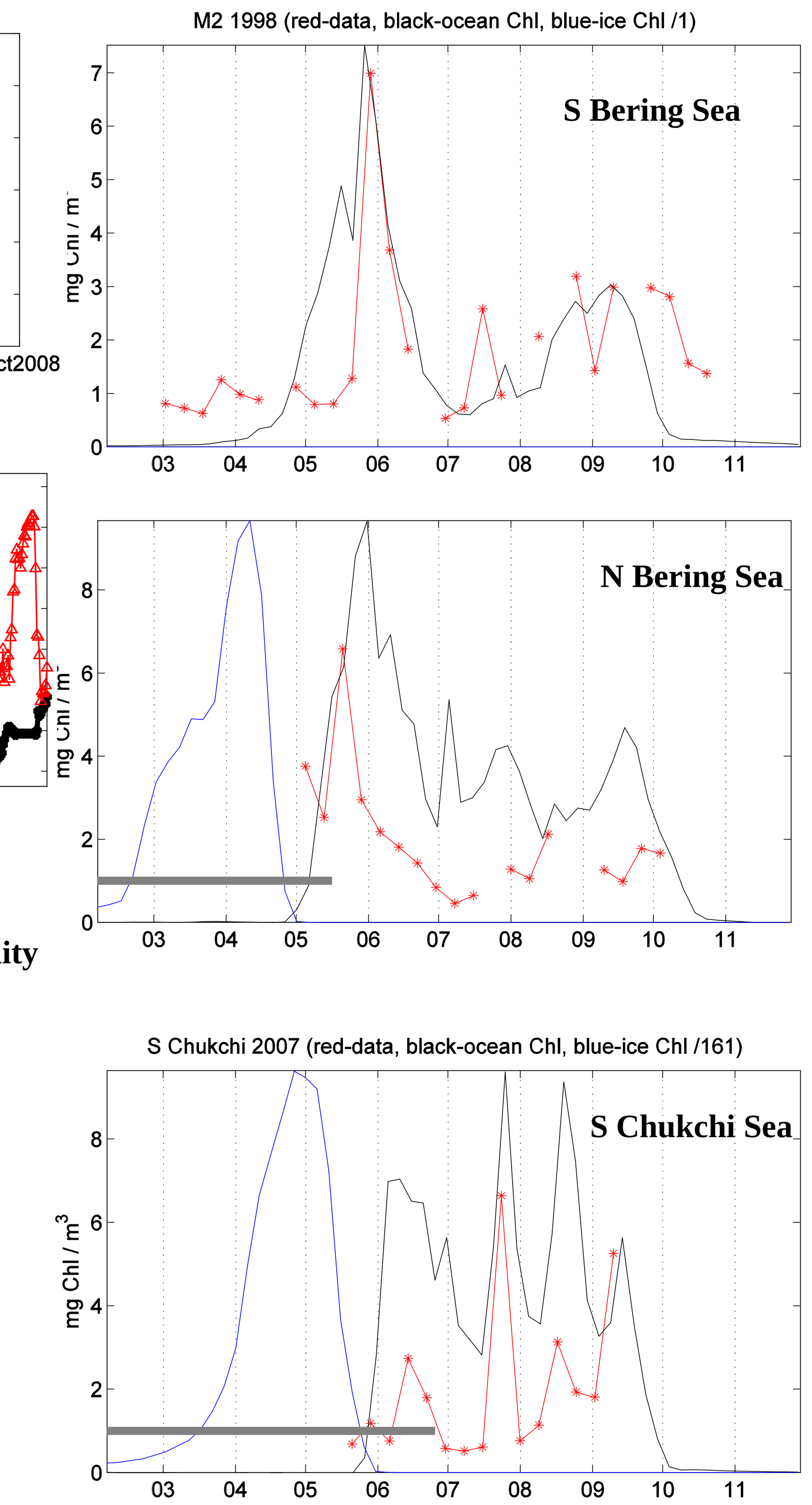

Figure 11. Seasonal cycle of modeled sea ice algae (blue), sea surface phytoplankton (black) vs. SeaWiFS Chl-a (red). The thick grey line indicates the presence of sea ice.

Summary

The Arctic sea ice algal production, although smaller than ocean algal production, is an ecologically important source of food to the upper trophic level during the long winter before ice melt. In this study, an ice algal ecosystem model was added to fully couple with the global physical model POP-CICE and open ocean pelagic ecosystem model. Forced by atmospheric data from NCEP, the physical model well captured the seasonal and interannual variations of northern hemispheric sea ice extent and areas by satellite remote sensing data in model period of 1992-2007. A seasonal cycle of ice algal production in March to May and subsequent ocean production from May to September in the Arctic was simulated and compared reasonably well with observational knowledge in the region. Overall, the simulated open-ocean upper 100m carbon production within the Arctic Circle was 413 Tg C/yr in 1998-2006, close to remote sensing derived estimate of 419Tg/yr but with higher interannual variations. The mean sea ice algal production in the northern hemisphere was 21.3 Tg/yr from 1992-2007, which is in the range of multi-observational estimations of 9 to 73 Tg/yr by in-situ measurements. In the Pacific Arctic, the spatial distribution of modeled climatologic annual carbon production in both sea ice and ocean are highest in the Bering Sea and gradually down the lowest in the central Arctic, which agrees well with observations in the regions. The model captured the observations on phytoplankton growth rate by size group that small phytoplankton carbon production rate in August was lower than that of the large phytoplankton in the Chukchi Sea shelf but higher in the Canadian Basin.

The surface pCO2 under sea ice cover are underestimated in the model. Sensitivity study showed that increase of sea ice permeability of CO2 may reduce the bias, but more observations are needed to determine sea ice permeability under different sea ice conditions and temperature ranges.

There are significant changes of the seasonality of primary production between the subartic and arctic seas. When we go north from the south Bering Sea to the Chukchi Sea, sea ice algal blooms becomes larger and lasts longer and phytoplankton blooms turns later (Fig 11). The seasonality of the coupled ice and pelagic production is still understudied, due to lack of observations and shorter period of open water time and less clear sky available for remote seasoning than the lower latitude.

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